Primordial Stellar Populations and The Next Generation Space Telescope

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(Based on work done in collaboration with Massimo Stiavelli, Harry Ferguson, and Peter Stockman)

The Next Generation Space Telescope: NGST at a Glance

- NASA+ESA+CSA joint project
- 6-meter class primary mirror
- 0.6-10+ µm wavelength range
- 5 year mission life (10 year goal)
- Passively cooled to <50K
- L2 orbit
- To be launched 2010
Why NGST is better than HST & Ground!

- A 6+ m telescope is required to probe the origins of stars and galaxies at large redshifts (early days).
- A cooled telescope provides $10^3$ to $10^8$ lower background.
- NGST imaging is diffraction-limited over $>10$ arcmin$^2$ FOV.
NGST will work at the Second Lagrange Point

- Metastable orbit, 1.5 million km from Earth.
- Solar radiation pressure is dominant torque.
- Thermally stable.
- 10 Mbs downlink is straightforward.
- Orbit corrections every month
NGST Telescope Concepts

Selected Sept 10, 2002

Primordial Stellar Populations
## NGST Science Instruments

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Description</th>
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<tr>
<td><strong>NIRCam</strong> (NASA)</td>
<td><strong>Near-IR and visible camera</strong> sensitive over the 0.6-5 micron wavelength range 4'x4' field of view 0.04&quot; pixels (lambda/2 D) at 2.4 micron possibly a R=100 spectral capability (slit+grism) possibly a coronographic capability</td>
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<tr>
<td><strong>NIRSpec</strong> (ESA)</td>
<td><strong>Multi-object dispersive spectrograph (MOS)</strong> sensitive over the 1-5 micron wavelength range &gt; 3'x3' field of view <del>0.1&quot; pixels R</del>1000 spectral capability, maybe an R~100 capability capable of observing &gt;100 objects simultaneously probably with MEMs (micro-electro-mechanical) technology</td>
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<tr>
<td><strong>MIRI</strong> (ESA/NASA)</td>
<td><strong>Mid-IR camera and slit spectrograph</strong> sensitive over the 5-28 micron wavelength range 2'x2' field of view imaging or R=1500 slit spectrograph a preference for a single focal plane array</td>
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<tr>
<td><strong>FGS</strong> (CSA)</td>
<td><strong>Fine Guide Sensor:</strong> Enable stable pointing at the milli-arcsec level sensitivity and field of view to allow guiding with 95% probability at any point on the sky</td>
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NGST – Who does What / Who’s Who

**Project Lead**: NASA/GSFC, Project Sci. John Mather

**Science & Operations Center** (SOC): STScI, Project Sci. Peter Stockman

**Telescope**: Prime Contract TRW/Ball (September 10, 2002).
- Subcontractor selection for primary mirror, sunshade, etc. TBD.

**Integrated Science Instruments Module**: NASA/GSFC ISIM Sci. Matt Greenhouse

**NIRCam**: team led by the U. of AZ-Tucson, with PI Marcia Rieke.

**NIRSpec**: ESA with a primarily European science team.

**MIRI**: 50/50 NASA and a *European consortium* (managed by ESA).
- ESA MIRI science team led by Gillian Wright (UK-ACT)
- US MIRI science team led by George Rieke, U. of AZ-Tucson.

NGST (JWST) Science Working Group

*Members of the JWST Science Working Group work in collaboration with the JWST Project, NASA Headquarters, and the astronomical community to provide input during the formulation (Phase A/B) and launch phases of JWST.*

*The Science Working Group will help provide astronomy community input on questions relating to the science mission of JWST, and will help disseminate information about JWST to the community.*
**NGST (JWST) Science Working Group**

<table>
<thead>
<tr>
<th>Name</th>
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<tbody>
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<td>Marcia Rieke</td>
<td>Univ. AZ, NIRCam Principal Investigator</td>
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<td>Massimo Stiavelli</td>
<td>STScI, Interdisciplinary Scientist</td>
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<td>Peter Stockman</td>
<td>STScI, STScI Science &amp; Operations Center Head</td>
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<td>Rogier Windhorst</td>
<td>AZ State Univ., Interdisciplinary Scientist</td>
</tr>
<tr>
<td>Gillian Wright</td>
<td>UK-ACT, ESA MIRI Science Rep.</td>
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NGST Science Goals

- Cosmology and the Structure of the Universe
- The Origin and Evolution of Galaxies
- The History of the Milky Way and Its Neighbors
- The Birth and Formation of Stars
- The Origins and Evolution of Planetary Systems
NIRCam Science Goals

A Formation of galaxies, from the first luminous massive condensations of material(A1) through the reionization(A2) of the Universe, to the assembly of galaxies and clusters and the development of morphological types (A3).

B Formation of stars and brown dwarfs, from twice the mass of Jupiter to the mass of the sun (1000 M_J) (B). We will probe the collapse of pre-stellar cores and test current ideas that the collapse is influenced by the local Jean’s mass (near 1 M_⊙) and by opacity-limited fragmentation (near 10 M_⊙).

C Planetary systems from birth to maturity. We will use coronagraphy to image and obtain spectra of debris disks(C) and compare their properties with those of our own counterpart, the Kuiper Belt. We will image and obtain spectra of massive giant planets around nearby stars, to determine their relation to debris disk structure and their atmospheric properties.
Seeking the origins of the Universe

• Observations of very distant galaxies can tell us how the Universe formed and evolved

• In particular:
  - How matter “coagulated” into galaxies
  - What type of stars were formed first
  - How did they evolve and enrich their environments of heavy elements
The Formation and Evolution of Galaxies

- What were the first sources of light in the Universe?
- How were luminous parts of galaxies assembled?
- How did the Hubble sequence of galaxy morphologies form?
- How do galaxies interact with their environment?
- What are the global histories of star-formation, metal enrichment, and gas consumption?
- What is the relationship between active galactic nuclei and their host galaxies?

When? … and what are the baryons doing?

z = 1000

z = 0
The Hubble Deep Field

Williams et al. (1996)
Distant Galaxies in the HDFs

- Galaxy sizes were smaller at higher redshifts (or number of small bright objects larger).
- Fraction of irregular and multiple component systems increases with redshift.
A galaxy building block at $z \approx 6$?

Combined HST-WFPC2 and Keck observations have revealed the most distant dwarf galaxy ever found

Gravitationally lensed ($\times 33$) by the Abell 2218 galaxy cluster, the small red galaxy is estimated to be at a redshift $z=5.6$, to have a mass of about $10^6 M_\odot$, and a young stellar population as young as 2-3 Myrs.

R. Ellis et al. 2001
Searches for high-z galaxies

- Lyman-break galaxies (i.e. blue continuum with sharp short wavelength cutoff), e.g. Steidel & Hamilton (1992) + … Giavalisco et al. (1994) + …

- Strong Lyman-\(\alpha\) emitters, e.g.,
  - Blank field surveys (Hu et al. 1991… Cowie & Hu 1998, …)
  - LALA survey (Malhotra & Rhoads 2002)
  - \(z \approx 2.4\) Ly-\(\alpha\) search (Stiavelli et al. 2001)

- High photometric redshifts, e.g. Lanzetta et al. (…) revealed galaxies up to \(z \approx 13\) (!?) in the HDFs
The NGST “Deep Field”
(simulation: I, J & K bands, 30 hrs, 2´×2´)

Im & Stockman 1998
Simulated NGST Deep Field
$(30'' \times 30'')$
Simulated Deep Field Observations (30″×30″) Ground-based (left) and NGST (right)
Primordial Stars?

**Question:** How do I recognize primordial stellar populations?

**Answer:** I check that there is no sign of metal pollution in their spectra: the *Next Generation* is expected to have $Z \geq Z_{\text{sun}}/1000$, so that $I([\text{OIII}]5007) \geq I(\text{H}\beta)/10$. 

Primordial Stellar Populations 21
Primordial Stars are expected to be:

- Metal free (Z=0)
- Hot (T_{eff} \sim 100,000 \text{ K})
- Formed in \sim 10^6 \text{ M}_\odot clouds
- Massive (>>10 \text{ M}_\odot, possibly >100\text{M}_\odot)

Low metallicity stars are hotter

Tumlinson & Shull (2000)
Low metallicity stars are **hotter**

Tumlinson & Shull (2000)

![Graph showing spectrum of Pop III and Pop II stars](image-url)
Zero-metallicity stars: Ionizing Photon Fluxes for HI, HeI and HeII

Tumlinson & Shull (2000)
The spectra of Population III (Z=0) and Extreme Population II (Z=Z_{\odot}/1000) Massive Clusters for a Salpeter IMF with $M_{up} = 90M_{\odot}$

Tumlinson & Shull (2000)
Population III stars can be very massive and are all very hot

Baraffe et al. (2001)
The *effective temperatures* of massive Pop III stars are about *twice as high* as those of Pop I stars.

Bromm *et al.* 2001
The spectra of massive Population III stars are very similar to black-bodies

Bromm et al. (2001)
How to detect *primordial stellar populations*?

- **High** $T_{\text{eff}}$ values imply **low optical-NUV fluxes**, about 3-8 times lower than in the local Universe

- On the other hand, the **ionizing fluxes** are **high**

- Therefore, *detection of primordial stars* will be possible through the study of *associated HII regions*.
The properties of the surrounding HII regions are:

- Highly ionized gas with presence of He$^{++}$
- High electron temperature $T_{\text{eff}} > 20,000$ K
- No metal ions
- No dust absorption
Model calculations for local Universe and primordial 
HII regions

The calculations were made using CLOUDY90 (Ferland et al. 
1998), adopting $n_e = 10^2 \text{ cm}^{-3}$ and scaled solar abundances.

Primordial Stellar Populations
An optical image of a *primordial HII region* will display:

- Fainter blue stars
- Red-orange nebula
- No dust absorption
Present Day HII Region

Primordial HII Region
The UV/optical spectrum is characterized by:

- Strong HI and HeI emission lines
- Moderately strong HeII lines
- No metal lines
- Flatter UV continuum
In particular we expect:

• Strong Lyα emission $L(\text{Ly}\alpha) \sim 0.46L_{\text{tot}}$
  $W_{eq}(\text{Ly}\alpha) \sim 3000\text{Å}$

• “Intense” HeII lines $I(1640) \sim I(\text{H}\beta)$

• Flatter UV continuum (2q emission)

• Steep Balmer decrement $H\alpha/H\beta \sim 3.2$
HII Region Electron Temperature

Primordial Stellar Populations
Model calculations made using CLOUDY90 (Ferland et al. 1998), adopting $n_e=10^2$ cm$^{-3}$ and scaled solar abundances.
The Ly-α intensity is considerably higher at low metallicity because of collisional excitation 1s-2p
The Ly-α equivalent width increases strongly at low metallicities because:
(a) the line intensity increases and
(b) the continuum flux decreases
The intensity of the [OIII] 5007Å line increases \textit{linearly} with O abundance at low metallicities.
Indeed, the [OIII] 5007Å line intensity is roughly proportional to the Oxygen abundance in Blue Dwarf Galaxies.

\[ \frac{I([\text{OIII}]5007)}{I([\text{OII}]3727)} \]

- $> 5$
- $2.5 - 5$
- $< 2.5$

[Data from Izotov & Thuan 1999]
The first generation supernovae pollute their primordial clouds

- The first supernova will eject at least 10 $M_\odot$ of metals
- The ejecta will be stopped in about 1 Myr inside the parent cloud whose mass is about $10^6 M_\odot$
- Correspondingly the cloud will be polluted to a level of about $Z \approx 0.00001 \approx Z_\odot/2000$
- Subsequent SNe will pollute further, up to as much as $Z \approx Z_\odot/200$
Metal Yield from Primordial Type II Supernovae

Oh et al. (2001), adapted from Heger & Woosley (2002)
The first generation supernovae enrich a primordial cloud to $Z \geq Z_\odot/1000$, which sets the stage for

The Next Generation

categorized by revealing properties

• Metal lines are present and detectable, e.g. [OIII] 5007Å with $I(5007)/I(H\beta) \geq 0.1$
• Dust may form and absorb as much as 30% of the Ly-\(\alpha\) line intensity, so that $L(MIR-FIR) \sim 0.15L_{\text{tot}}$
THE BIG QUESTION:

“When is low metallicity low enough?”

Or “If we do not detect metal lines in the HII region spectrum, how will we be sure that the gas is metal free?”

THE ANSWER:

“There are no metals if $\frac{I(5007\text{Å})}{I(H\beta)} < 0.1$”
Local Universe and “second” generation HII regions
“second” generation and “primordial” HII regions
Spectra of primordial HII regions ionized by 50,000K and 100,000K stars
**Pristine stars + pristine gas**

**Pristine stars + polluted gas**

**Enriched stars + enriched gas**

**Local universe stars + gas**
The spectrum seen through Broad-band Photometry ($\lambda/\Delta\lambda=4$)
Can we see Ly-\(\alpha\) before re-ionization?
Lyman-\(\alpha\) transmission through neutral IGM
(Gunn & Peterson 1965)

Observed Ly-α Luminosity: a considerable fraction of the emitted one!

Model calculations assuming a Ly-α line width of 250 km s$^{-1}$
Do we have the means to study such distant stars?

• “Yes” and “No”…

• **YES**, we can detect distant galaxies → Ly-α

• **NO**, we cannot characterize them fully, **YET** → NGST will be able to do so
Expected NGST Sensitivity
Observing a $10^6 \, M_\odot$ starburst with NGST

Limiting fluxes for exposure time $4 \times 10^5$ s and $S/N=10$
Limiting total luminosities and star formation rates to detect emission lines with an exposure time of 10 hours at S/N=5 ([OIII] and HeII) and S/N=10 (Hα, Hβ and Lyα)
Spectroscopy with NGST

will be able to detect an [OIII]5007A line \( \frac{I(5007)}{I(H\beta)} \sim 0.1 \) with an exposure time of 10 hours at a S/N=5 level

up to \( z=10 \) for SFR \( \geq 0.1 \, M_\odot \, yr^{-1} \)

up to \( z=15 \) for SFR \( \geq 1 \, M_\odot \, yr^{-1} \)

allowing us to discern \textit{bona fide} primordial stellar populations from those polluted by early supernovae
Studying Primordial Stellar Populations

- Search for Ly-\(\alpha\) dropouts in I,J,H,K bands
- strong Ly-\(\alpha\) emitters
  \(\rightarrow\) candidates at redshifts \(>6\) ground-based 8-10m
  HST (Rhoads et al., Cycle 11)
  NGST (NIR: grism, imaging)

- Study the UV and optical rest-frame spectrum of suitable candidates with NGST in the NIR/MIR
  “strong” HeII 1640 line \(\rightarrow\) top-heavy IMF
  “detectable” [OIII] line \(\rightarrow\) next-gen stars
Conclusions

- It is possible to discern *truly* primordial stellar populations from next generation stars ([OIII] 5007Å)
- It is possible to identify the properties of the dominant stars (HeII 1640Å)
- It is possible to measure metallicities of galaxies up to redshifts 10-15

*NGST* will be able to do all of this